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Measuring carbon dioxide emission performance in Chinese provinces: A parametric approach

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ABSTRACT

This paper looks at carbon dioxide (CO_2) emissions from the point of view of production theory and proposes a new total factor CO_2 emissions performance index. This is done using directional distance function followed by stochastic frontier analysis techniques in order to estimate the index. Based on this, it studies on CO_2 emission performance, emission reduction potential and influences of regulatory policies in Chinese provinces. The main conclusions include the following: (1) CO_2 emission performance in each province is high in southeastern coastal areas but low in central and western inland regions with differences increasing rapidly after 2001. (2) The relationship between CO_2 emission performance and emission reduction potential can be divided into four types; high performance-high potential, high performance-low potential, low performance-high potential and low performance-low potential. (3) Regulations concerning emission reduction do not sacrifice efficiency but actually facilitate long-term CO_2 emission performance.

Contents

1. Introduction

China is the largest developing country and its economy has increased continuously and rapidly since the reform and opening-up policy was implemented. Gross domestic product (GDP) has increased on average by more than 9% each year. This rapid growth of the Chinese economy has however been achieved by huge consumption in energy resources, such as coal and oil, leading to a great deal of carbon dioxide (CO_2) emissions. According to the 2011 statistical report of the *International Energy Agency*, Chinese energy consumption increased by 120% from 2000 to 2010 and its proportion of global consumption shot up from 9.1% to about 20%. China is now the second largest energy consumer in the world with the result that CO_2 emissions have likewise increased from 12.9% to about 23%. It has become

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the largest CO_2 emitter and CO_2 emissions per capita currently exceed the world average.

At present, China is in a period of rapid industrialization and urbanization, when both urban population and simultaneous large-scale infrastructure projects increase the demands for energy growth in parallel with the production of CO_2. CO_2 emissions are predicted to rise for many years to come. Meanwhile, the United States and the European Union (EU) have asked China to join in a post Kyoto global emission reduction agreement. At the same time, small island countries and some of the least developed countries also hope that China can further reduce emissions. China is facing ever stronger diplomatic and public opinion pressure regarding international CO_2 emission reductions.

Facing greatly increased CO_2 emissions, the Chinese government has taken emission reduction measures in many areas including the establishment of mandatory emission reduction targets. Before the 2009 Copenhagen Climate Change Conference, China pledged to reduce CO_2 emissions per unit of GDP (CO_2 intensity) by 40–45% by 2020. Later, the government not only adopted the target as a binding goal for economic and social development plans but also regarded the reduction of 17% in CO_2 intensity as a task of 'the 12th Five-Year Plan'. Furthermore, in order to rapidly develop new energy sources and reduce the proportion of fossil energy consumption, the Chinese government formulated a number of supportive policies. It also announced that the proportion of non-fossil energy consumption should be increased from less than 10% currently to 15% in 2020.

In general, the outlook for CO_2 emissions in China is not optimistic, as there are both international pressures and domestic pressures. Although the central government has formulated some plans and polices as well as taken emission reduction actions in provinces, industries and key enterprises, the economic growth pattern of China mainly focuses on extensive forms. Energy technology equipment, technical know-how and management of CO_2 emission reduction are all still relatively backward. Besides, a bottleneck of technology and capital for energy saving and emission reduction still exists. Therefore, there is an urgent need to improve CO_2 emission performance.

As the foundation and premise on which the estimation of CO_2 emission performance, measuring methods and index selection have been gradually discussed. Different points of view, different time periods and different perspectives have led to numerous international commonly used indexes of CO_2 emission performance. These are shown in Table 1.

For the indexes above mentioned, Mielnik and Goldemberg [13] proposed using CO_2 emission per unit of energy as the standard by which developed countries respond to climate change and evaluate economic development. Ang [14], on the other hand, felt that the change of energy intensity basically reflected CO_2 emissions when studying climate change and that the two indexes could almost be treated as the same. Sun [15] proposed that CO_2 intensity should be the ideal index when energy source policies of a country and the effect of carbon emission reduction are evaluated. In other papers, CO_2 per capita has drawn many scholars' attention [16,17]. Based on their systematic summarization of advantages and disadvantages of the above indexes, Zhang et al. [18] proposed some new evaluation indexes, such as industrialized accumulated CO_2 per capita and CO_2 emission per capita per unit of GDP.

Basically, these indexes of CO_2 emission performance measure either the total amount or the ratio of two related variables to each other. Therefore, they do not reflect the process by which CO_2 is produced and neglect the effects of energy structure, economic development and element replacement [19]. In this they can be called single factor indexes. Using the thoughts of environmental performance evaluation [20,21], Zhou et al. [22] proposed a total factor CO_2 emissions performance (TFCP) index and measured the performance of 18 main CO_2 emitters throughout the world using a non-parametric method of data envelopment analysis (DEA). Later, based on the similar ideas, Guo et al. [23] calculated CO_2 emission performance in each province of China from 2005 to 2007, with the corresponding emission reduction potential also given.

As the DEA method does not take random factors into consideration and its calculation of efficiency is easily affected by exceptional values, the parametric method of stochastic frontier analysis (SFA) was developed by Aigner et al. [24]. It has also been applied to the fields of environmental efficiency and energy efficiency. For example, Murty and Kumar [25] used SFA to measure the environmental efficiency of manufacturers who cause water pollution in India. Murty et al. [26] then measured and analyzed the dynamic environment efficiency of five Indian thermal power plants using the same method. Meanwhile, Zhou et al. [27] established a model for energy efficiency based on SFA and mainly took OECD countries as examples to compare the difference of measured results between DEA and SFA.

In the literature, the measurement of CO_2 emission performance has mainly focused on a single factor index like CO_2 intensity [5]. However, the application of TFCP based on production theory, which accords with reality better, has been little used. Most of the specific calculations for TFCP also adopt nonparametric DEA methods [22,23]. This paper will attempt to establish a new TFCP index using directional distance function (DDF) and to estimate this index using the parametric method of SFA. An empirical study of CO_2 emission performance in Chinese provinces using the above approach is also presented.

The rest of this paper is organized as follows. Section 2 focuses on methodology. The steps for establishing TFCP and estimating DDF is presented in this part. Section 3 presents the empirical study in

Table 1
Common indexes of CO_2 emission performance.

Index	Basic definition	Author and applied country (region)
Total CO_2 emission	Calculated by taking a country (a region) as a unit	Wang et al., China [1] Stern, all over the world [2] World Bank, all over the world [3]
CO_2 intensity	The ratio of CO_2 emission to GDP, that is, CO_2 emission per unit of GDP	Greening et al., 10 countries of OECD [4] Fan et al., China [5]
CO_2 productivity	The ratio of GDP to CO_2 emission, that is, CO_2 productivity is the reciprocal of CO_2 intensity	Beinhocker et al., all over the world [6] Pan and Zhang, China [7]
CO_2 emission per capita	The ratio of CO_2 emission to population	Stretesky and Lynch, 169 countries [8] Jobert et al., 22 countries of EU [9]
Embodied CO_2 emission in trade	Calculation is implemented by taking CO_2 emission transfer in international trade	Shui and Harriss, America and China [10] Peter and Hertwich, 87 countries [11] Su and Ang, China [12]

which the index proposed in Section 2 is used to analyze and discuss CO_2 emission performance and carbon reduction potential in Chinese provinces. Section 4 sets out the main conclusions.

2. Methodology

2.1. Environmental production technology and directional distance function

It was Färe et al. [28] who first put forward the idea of environmental production technology. They believed that, in a common productive process, element input is always accompanied by by-products like waste water, waste gas and waste residue in addition to the desirable output, i.e., there is undesirable output. We are concerned with CO_2 emission performance in this paper, so the production framework in a certain region can be supposed as [22] and [29]. The inputs of capital (k), labor force (l) and energy (e) can form one desirable output of GDP (y) and one undesirable output of CO_2 (c). The production technology can be described as the following equation of whose output set $P(k,l,e)$ can:

$$P(k,l,e)=\{(k,l,e,y,c):(k,l,e)\ can\ produce\ (y,c)\} \tag{1}$$

Output set $P(k,l,e)$ has the properties of close, bounded and convexity as well as the strong disposability of input and desirable output, which are the same as the conventional production technology. To model joint production of desirable and undesirable output, $P(k,l,e)$ has two additional axioms; weak disposability and null-jointness [30,31]. Weak disposability indicates that the reduction of CO_2 is realized at the cost of economic development and only proportionate reduction of the two outputs is possible. That is, if $(y,c)\in P(k,l,e)$ and $0\le\theta\le 1$, then $(\theta y,\theta c)\in P(k,l,e)$. Null-jointness states that the realization of economic development must be accompanied by the generation of CO_2 and the only way to avoid emissions is to stop all production activities, i.e., $(y,c)\in P(k,l,e)$ and $c=0$, then $y=0$.

To construct the CO_2 emission performance index in the framework of production theory and following Färe et al. [32], we define a DDF that can not only increase GDP but also reduce CO_2, which is shown in Eq. (2). This is neither consistent with the ideas of traditional Shephard distance function, which asks to realize simple maximum output or minimum input, nor the same as the proposals of Zhou et al.[22], which ask to reduce only CO_2 emissions.

$$D(k,l,e,y,c;g)=\sup\{\beta:(y+\beta g_y,c-\beta g_c)\in P(k,l,e)\} \tag{2}$$

where $g=(g_y,g_c)$ is the direction vector, which indicates the expansion of GDP in the direction of g_y and the reduction of CO_2 in the direction of g_c. β presents the maximum proportion of this expansion and reduction. It follows that the minimum CO_2 emission in the evaluated region theoretically is $(1-D(k,l,e,y,c))c$, therefore CO_2 emission performance can be defined as shown below:

$$TFCP=1-D(k,l,e,y,c) \tag{3}$$

In accordance with definitions of DDF and TFCP, it is known that $0<TFCP\le 1$, and the larger the value of TFCP is, the higher CO_2 emission performance for the evaluated region is. On the other hand, the smaller the value of TFCP is, the lower the performance is. When TFCP=1, it is shown that the region just locates on the production frontier and its performance is the best of all regions.

Fig. 1 is a simple schematic diagram of DDF and the measurement of CO_2 emission performance. Point A stands for a certain region in the production technology set $P(k,l,e)$, while segment OI and segment OE represent GDP and production quantity of CO_2 in this region respectively. To satisfy the conditions of Shephard distance function, the two kinds of output are handled symmetrically and point A moves towards point D to maximize output. Obviously, this mode indicates economic expansion but CO_2 emissions also rapidly increase. When CO_2 emission performance is taken into consideration fulfilling the conditions of DDF, point A moves towards point C, which not only reduces CO_2 emissions (the emission reduction is GE) but also shows economic development (the added quantity is HI). This is the favored state of 'good and rapid' development in this region, which is also superior to the situation Zhou et al.[22] proposed in which CO_2 only is reduced (point A moves towards point B).

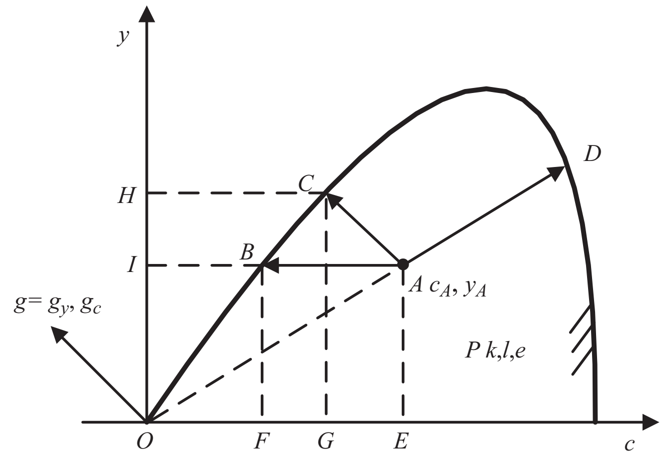

Fig. 1. Directional distance function.

2.2. Estimation of directional distance function

The specific values of CO_2 emission performance index are realized by the solution to DDF. DEA and SFA are the common methods. DEA is convenient for calculation and it is used to evaluate energy efficiency [33], environmental efficiency [34], bank efficiency [35] and so on, although it cannot deal with random uncertain factors [27,36]. On the other hand, the SFA method, which is parametric, does consider random errors in the resolution of inefficiency factors and, as the estimated results of efficiency are stable, it has been applied to many fields [37,38]. Therefore, SFA is used in this paper.

When parametric approaches are used to calculate distance function, it is necessary to set the specific form of the function, including Cobb-Douglas, translog and quadratic forms. According to [32], the form of distance function in this paper is set as the translog form. This is shown in the following equation , where v is a random variable accounting for statistical noise and errors of approximation.

$$\begin{aligned}D(k,l,e,y,c)&=\beta_0+\beta_k k+\beta_l l+\beta_e e+\beta_y y+\beta_c c+\beta_{kl}kl\\&+\beta_{ke}ke+\beta_{ky}ky+\beta_{kc}kc\\&+\beta_{le}le+\beta_{ly}ly+\beta_{lc}lc+\beta_{ey}ey+\beta_{ec}ec+\beta_{yc}yc\\&+\frac{1}{2}\beta_{kk}k^2+\frac{1}{2}\beta_{ll}l^2+\frac{1}{2}\beta_{ee}e^2+\frac{1}{2}\beta_{yy}y^2+\frac{1}{2}\beta_{cc}c^2+v\end{aligned} \tag{4}$$

DDF also has translation property [32], which can be denoted as Eq. (5). This property means that if GDP is increased by α in the direction of g_y and CO_2 is decreased by α in the direction of g_c, then the value of the resulting distance function will be more efficient by the amount α. Therefore, setting the amount of such increase and decrease as c, it follows the distance function in

region i in the period of t satisfies as shown below:

$$D(k,l,e,y+\alpha g_y,c-\alpha g_c)=D(k,l,e,y,c)-\alpha \tag{5}$$

$$D(k_{it},l_{it},e_{it},y_{it}+c_{it},0)=D(k_{it},l_{it},e_{it},y_{it},c_{it})-c_{it} \tag{6}$$

Following the translog form of DDF, Eq. (7) about $D(k_{it},l_{it},e_{it},y_{it}+c_{it},0)$ is obtained.

$$\begin{aligned}D(k_{it},l_{it},e_{it},y_{it}+c_{it},0) &= \beta_0+\beta_k k_{it}+\beta_l l_{it}+\beta_e e_{it}\\ &+\beta_y(y_{it}+c_{it})+\beta_{kl}k_{it}l_{it}+\beta_{ke}k_{it}e_{it}+\beta_{ky}k_{it}(y_{it}+c_{it})\\ &+\beta_{le}l_{it}e_{it}+\beta_{ly}l_{it}(y_{it}+c_{it})+\beta_{ey}e_{it}(y_{it}+c_{it})\\ &+\frac{1}{2}\beta_{kk}k_{it}^2+\frac{1}{2}\beta_{ll}l_{it}^2+\frac{1}{2}\beta_{ee}e_{it}^2+\frac{1}{2}\beta_{yy}(y_{it}+c_{it})^2+v_{it}\end{aligned} \tag{7}$$

Substitute Eq. (7) into Eq. (6) so that Eq. (8) is obtained after settlement.

$$\begin{aligned}-c_{it} &= \beta_0+\beta_k k_{it}+\beta_l l_{it}+\beta_e e_{it}+\beta_y(y_{it}+c_{it})+\beta_{kl}k_{it}l_{it}\\ &+\beta_{ke}k_{it}e_{it}+\beta_{ky}k_{it}(y_{it}+c_{it})+\beta_{le}l_{it}e_{it}+\beta_{ly}l_{it}(y_{it}+c_{it})\\ &+\beta_{ey}e_{it}(y_{it}+c_{it})+\frac{1}{2}\beta_{kk}k_{it}^2+\frac{1}{2}\beta_{ll}l_{it}^2+\frac{1}{2}\beta_{ee}e_{it}^2\\ &+\frac{1}{2}\beta_{yy}(y_{it}+c_{it})^2+v_{it}-u_{it}\end{aligned} \tag{8}$$

where $u_{it}\equiv D(k_{it},l_{it},e_{it},y_{it},c_{it})$ is a non-negative variable which represents the inefficiency when CO_2 emission performance in i region in the period of t is evaluated. Following [32], related coefficients satisfy Eq. (9).

$$\beta_y-\beta_c=-1,\ \beta_{yy}=\beta_{cc}=\beta_{yc},\ \beta_{kc}=\beta_{ky},\ \beta_{lc}=\beta_{ly},\ \beta_{ec}=\beta_{ey} \tag{9}$$

Eq. (8) is a typical SFA model, which includes input, output, random variable and inefficiency variable. Therefore, the SFA model can be used to solve inefficiency. Then, according to Eq. (3), the value of CO_2 emission performance in i region in the period of t can be obtained, i.e., $TFCP_{it}=1-u_{it}$.

3. Empirical application

3.1. Data

Based on the availability of data, this paper takes input and output data in 28 Chinese provinces from 1995 to 2009. Hainan and Tibet are excluded because of missing data, while Chongqing and Sichuan are counted together. The data on GDP, energy and labor are derived from the *China Statistical Yearbook* and capital stock is estimated by the perpetual inventory method [39]. The data on CO_2 emissions for each province are estimated from the energy consumption breakdown by each fuel category [5,23,29]. To eliminate the price effect, the variables of capital stock and GDP are deflated by the consumer price index in the year 2000. Table 2 displays the statistical description of input and output variables in 28 Chinese provinces from 1995 to 2009.

3.2. Parameter estimation

To calculate CO_2 emission performance in each province, it is essential to initially estimate each parameter in Eq. (8). Then, other parameters are reckoned according to Eq. (9). There are two random variables v_{it} and u_{it} in Eq. (8) which are complicated to estimate. A common assumption is that v_{it} satisfies half-normal distribution, i.e., $v_{it}\sim N(0,\sigma_v^2)$, and it is independent of u_{it} [36]; while the distribution of u_{it} consists of half-normal distribution, truncated normal distribution, exponential distribution and gamma distribution etc. This paper selects half-normal distribution. Then, the values of all parameters in Eq. (8) are estimated by maximum likelihood method, which are shown in Table 3.

Table 3 shows that the estimated values of most parameters pass statistical tests at 1% significance level. At the same time, it is found that the sign of CO_2 emission coefficient β_c is positive which shows the higher the emissions in the region is, the larger the corresponding efficiency loss is and the lower the performance is. When the sign of GDP coefficient β_y is negative, it shows that the larger the GDP in the region is, the lower the efficiency loss is, and while the higher the performance is. This is consistent with the basic ideas when the CO_2 performance index was

Table 2
Summary statistics of inputs and outputs.

Variable	Unit	Mean	Std. Dev.	Min	Max
Capital Stock(k)	RMB Billion(2000)	933.1	893.4	35.8	5523.6
Labor(l)	Million workers	23.4	15.8	2.3	68.2
Energy(e)	Million tons of coal equivalent (Mtce)	74.8	54.3	6.9	324.2
GDP(y)	RMB Billion(2000)	493.4	473.2	16.2	2841.8
CO_2(c)	Million tons (Mt)	231.6	178.6	14.9	1086.3

Table 3
Estimated results of parameters.

Variable	Parameter	Estimated value	Standard dev.	t-statistic	Variable	Parameter	Estimated value	Standard dev.	t-statistic
Constant	β_0	0.143	0.0094	15.2418[a]	ly	β_{ly}	0.0146	0.0289	0.5065
k	β_k	0.7146	0.0225	31.8098[a]	lc	β_{lc}	<u>0.0146</u>		
l	β_l	0.1267	0.0121	10.4536[a]	ey	β_{ey}	0.088	0.1242	0.7083
e	β_e	−0.2581	0.0448	−5.7648[a]	ec	β_{ec}	<u>0.088</u>		
y	β_y	−0.7209	0.0314	−22.9805[a]	yc	β_{yc}	−<u>0.185</u>		
c	β_c	<u>0.2791</u>			k^2	β_{kk}	−0.1262	0.0562	−2.245[a]
kl	β_{kl}	−0.0133	0.0236	−0.5633	l^2	β_{ll}	−0.086	0.0165	−5.2284[a]
ke	β_{ke}	−0.2298	0.0754	−3.0485[a]	e^2	β_{ee}	0.1916	0.1854	1.0335
ky	β_{ky}	0.1782	0.0496	3.5916[a]	y^2	β_{yy}	−0.185	0.0819	2.2596[a]
kc	β_{kc}	<u>0.1782</u>			c^2	β_{cc}	−<u>0.185</u>		
le	β_{le}	0.0527	0.0458	1.15	Log likelihood		486.84		

[a] indicates 1% significance level and values with underlines are obtained by Eq. (9).

established. Capital stock, labor force and energy can not only generate both desirable outputs and undesirable outputs directly or indirectly, they can also have complicated impacts on CO_2 emission performance as the signs of the corresponding coefficients are different.

3.3. Analysis and discussion

3.3.1. Analysis of performance

Using corresponding parameters, inefficiency of CO_2 emission in Chinese provinces in each period can be obtained, i.e., $u_{it} \equiv D(k_{it}, l_{it}, e_{it}, y_{it}, c_{it})$, and then the actual performance value calculated according to Eq. (3).

Fig. 2 presents average values of CO_2 emission performance in 28 Chinese provinces from 1995 to 2009, according to which it is found that performance in eastern coastal province, such as Guangdong, Shanghai, Fujian, Beijing and Liaoning is high; the value of TFCP in these provinces is above 0.80.In other words, the inefficient part of CO_2 emission in these provinces is lower than 20%. In addition, the value of TFCP in central and western provinces like Inner Mongolia, Xinjiang, Qinghai, Ningxia and Shanxi is lower than 0.70, while inefficiency is above 30%. Basically, the results that CO_2 emission performance is high in the east but low in central and western, while it is high in coastal regions but low inland, are the same as the existing conclusions [23].

This is especially true for Shanxi and Ningxia which have the lowest performance values of all provinces, 0.550 and 0.589 respectively. The two provinces have very high emissions, which may be related to the industrial structure of their heavy industries. Meanwhile, the value of TFCP in the other provinces is basically kept between 0.60 and 0.80.

In order to investigate the difference of CO_2 emission performance among Chinese provinces further, Fig. 3 provides the changes in standard deviation of performance values from 1995 to 2009. According to the figure, it is found that the difference in CO_2 emission performance between Chinese provinces from 1995 to 2000 is minor and that the standard deviation fluctuates slightly around 0.05. However, from 2001, the difference increases rapidly. As a result, the standard deviation in 2009 is above 0.20, which is about four times higher than that before 2001. This states that carbon reduction policies should not only look at the control of total amount but also consider existing differences among provinces. The principle of '*common but differential responsibility*' in Chinese provinces should be implemented and enhanced.

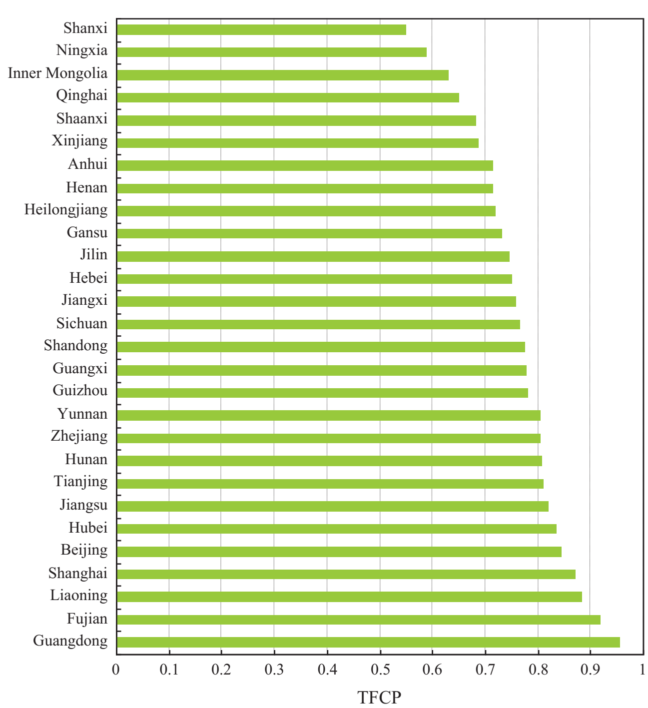

Fig. 2. Average of TFCP in 28 Chinese provinces.

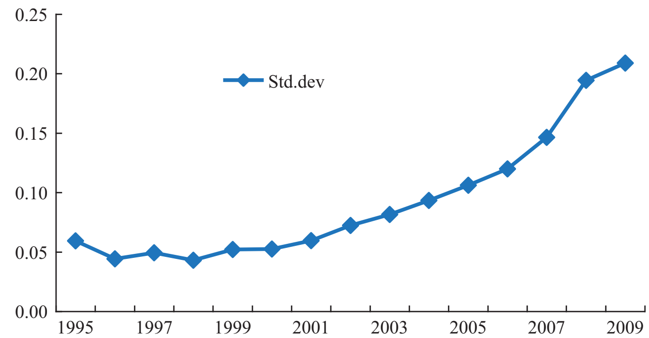

Fig.3. Changes of standard deviation of TFCP.

3.3.2. Analysis of emission reduction

The proportion of efficiency loss in each province can be judged according to the specific value of TFCP, but the absolute amount of redundant CO_2 emission, which is caused by inefficiency, still needs to be affirmed. In addition, this absolute amount results from two factors, one of which is the level of TFCP and the other is actual emission of CO_2 in Chinese provinces. The extra CO_2 emissions can be reduced on condition that input is not increased or economic output is not decreased. This gives the CO_2 emission reduction potential (CRP) in each province. Furthermore, we analyze the reduction potential of CO_2 in all 28 provinces during the sample period. It is found that the difference between target emissions and actual emissions increases rapidly from 2004. It increases from less than one half billion tons in 1995 to about 2 billion tons in 2009, which is four times larger than that in 1995. The potential of CO_2 emission reduction has a growth trend.

The reasons for this phenomenon may be that Chinese economic development changed into a pattern of low quality, low efficiency, low employment, high consumption, high pollution and high emission in the latter periods of the '10th Five-Year Plan' when steel, cement, electrolytic aluminums and coal industries developed rapidly. In 2005, heavy industry accounted for 69% of total industrial output value resulting in excessive industrialization and the rapid increase of CO_2 emissions.

Based on the analysis of total CO_2 emission reduction potential, we discuss the relationship between TFCP and CRP. The average levels of CO_2 emission performance and CO_2 emission reduction potential are regarded as the standard, then TFCP and CRP for the 28 provinces can be divided into four basic categories: low performance-low potential (Category 1), high performance-low potential (Category 2), high performance-high potential (Category 3) and low performance-high potential (Category 4), shown in Fig. 4.

Category 2 and category 4 show that there is a negative relationship between CO_2 emission performance and CO_2 emission reduction potential. In other words, in the eight provinces which belong to category 2, including Beijing, Tianjin and Shanghai, TFCP is high and CRP is low. Similarly, in the five provinces including Shanxi, Hebei and Henan, which belong to category 4, TFCP is found to below and CRP high. There is no corresponding relationship between TFCP and CRP in other provinces. Although

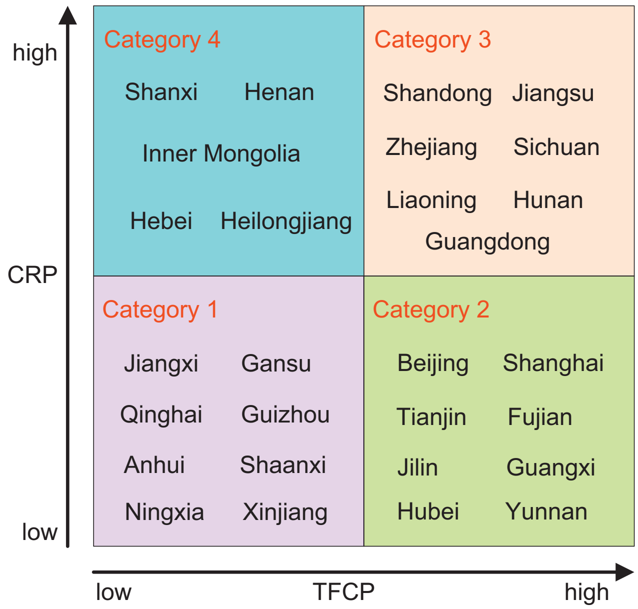

Fig. 4. Categories of TFCP and CRP.

the TFCP is high in seven provinces including Shandong, Jiangsu and Zhejiang, which belong to category 3, the CRP is higher than those provinces of category 1 and category 4, whose performance is low. The reason for this is that the total CO_2 emission in provinces of category 3 is huge; quite small efficiency losses will result in a great deal of CO_2 emissions. Therefore, though these provinces have favorable performance, the task of emission reduction is still great. They should especially pay attention to the long periods and continuity of emission reduction policies and actions. Total CO_2 emission in eight provinces is low, such as Qinghai, Ningxia and Xinjiang, which belong to category 1, so the emissions that can be reduced are not great even though performance is not high.

3.4. Analysis of regulation

The above analyses indicate that there is efficiency loss of CO_2 emission in most Chinese provinces, so that there is much emission reduction potential. To achieve the target of CO_2 emission reduction in 2020 and the period of the '12th Five-Year Plan', provinces will have to take action to regulate CO_2 emissions. Will the implementation of regulation policies sacrifice efficiency? To answer this question, we look at the relationship between CO_2 regulations and CO_2 emission performance.

According to the thought used to study the relationship between environment efficiency and water pollution [26], the model is set as Eq. (10) where u_{it} is the non-negative variable mentioned in Eq. (8), which represents the inefficiency of CO_2 emission in i province in the period of t. Besides, RI_{it} and CI_{it} stand for two variables of CO_2 emission regulations. RI_{it} is defined as the ratio of actual CO_2 emission in i province in the period of t to the maximum CO_2 emission in the same year and $0<RI_{it}\le 1$. It takes the value one for the region with the least compliance of regulation and approaches zero for the region with the maximum compliance or zero CO_2 emission. CI_{it} is defined as CO_2 intensity in i province in the period of t. The lower the value of CI_{it} is, the more effective the efforts to reduce CO_2 emission in this province is. T and ε_{it} represent the variables of time and random error respectively.

$$u_{it}=\alpha_0+\alpha_1 RI_{it}+\alpha_2 CI_{it}+\alpha_3 T+\varepsilon_{it} \tag{10}$$

Table 4
Results of panel data regression.

Variable	Parameter	Estimated value	Standard dev.	*t*-statistic
Constant	α_0	−0.0049	0.0174	−0.2830
RI	α_1	0.0966	0.0246	3.9255[a]
CI	α_2	0.0035	0.0011	3.0253[a]
T	α_3	−0.0133	0.0014	9.7602[a]
R^2=0.458 Sample=420				

[a] indicates 1% significance level.

A panel data regression model of random effects is used to implement the regression of Eq. (10), whose results are shown in Table 4. It is found that the coefficient of *RI* is positive and passes significance test at 1% level; that is, *RI* has positive correlation with the inefficiency of CO_2 emission. In other words, if a province enforces regulations more strictly, its inefficiency is lower and its actual performance is higher. This is consistent with Porter's assumption that environmental regulation can not only promote technological innovation but also improve efficiency [25,26,40]. Generally speaking, regulation policies will not result in efficiency loss but be an effective way to reduce CO_2 emissions.

In addition, the coefficient *CI* is also positive at a 1% significance level, which shows that the higher CO_2 intensity is, the lower CO_2 emission performance is. Contrarily, the lower CO_2 intensity is, the higher the performance level is. Furthermore, the coefficient of time variable, α_3, is positive, which presents CO_2 emission performance integral changes with time.

4. Conclusion

Measuring CO_2 emission performance is the basis for calculating reduction potential and formulating corresponding policies. This paper constructs a new index, TFCP by DDF and SFA. Based on this, it not only analyses CO_2 emission performance and CO_2 emission reduction potential in 28 Chinese provinces from 1995 to 2009, but also discusses the influence of reduction policies.

As a whole, CO_2 emission performance in southeastern and coastal provinces like Shanghai, Guangdong, Fujian and Beijing is higher than 0.80, while the performance in central and western provinces including Xinjiang, Inner Mongolia and Ningxia etc. is less than 0.70. It is obvious that CO_2 emission performance is high in the east but low in central and western China, while it is high in coastal regions but low inland. In addition, the differences between provinces in the sample period did not reduce but continued to increase after 2000. Therefore, to implement the CO_2 emission reduction targets, it is necessary to observe the principle '*common but differential responsibility*' when tasks are allocated to provinces.

Although CO_2 emission performance in Chinese provinces does not significantly change with time, the extra CO_2 emissions resulting from inefficiency increase noticeably. Redundant emissions for all 28 Chinese provinces in 2009 were about 2 billion tons. The main reason for this phenomenon is the rapid industrialization and urbanization of China. For the four categories of provinces, divided according to CO_2 emission performance and reduction potential, policy-makers should be concerned more with two: 'low performance-high potential' and 'high performance-high potential'. The reason for the former is that low performance causes a lot of CO_2 emissions that can be reduced, while provinces of the latter type are usually major CO_2 emitters; although their performance is high, their reduction potential is not low.

Regulating CO_2 emissions will not sacrifice efficiency. If the provinces strictly obey regulations, CO_2 emission performance will improve, which is consistent with Porter's hypothesis. Moreover, as

CO_2 intensity directly affects the level of performance, overall improvement in CO_2 emissions can be carried out from two aspects. Firstly, it is essential to continuously promote economic development, especially the development in western provinces, in order to reduce CO_2 intensity. Secondly, the formulation and implementation of regulation policies concerning CO_2 emissions should concentrate on innovation and improvements in the technology and management of CO_2 emission reduction.

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